Towards realistic Monte Carlo event generators

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Outline

- Introduction, many (!) motivations.
    - a main point: to distinguish between parameter and model uncertainties in neutrino interactions.
- Examples:
    - pion production in Δ region,
    - spectral function vs Fermi gas,
    - meson exchange current.
- NuWro.
- Discussion.

Monte Carlo simulations in neutrino experiments

- (i) flux,
- (ii) neutrino interactions,
- (iii) detector performance.

In this talk I am interested in the step (ii) only.

Monte Carlo event generators

In neutrino oscillation experiments MC is only a tool.

In dedicated neutrino cross section experiments like MINERvA a perspective should perhaps be more ambitious?!

MCs should contain best of our knowledge of cross sections (strictly speaking of models which are implementable, able to produce large numbers of events in a reasonable time).

Monte Carlo event generators – limitations

MCs cannot be better than our knowledge of neutrino cross sections. And this is rather poor.

- CCQE axial mass 1.05 or rather 1.35 GeV?!...
- a huge MC/data discrepancy in MiniBooNE π production measurements.
- ...

In the 1 GeV region cross sections are known with an accuracy of 20-30%.

A challenge for MINERvA to try to provide more accurate measurements!

Uncertainties: models and parameters

This is important to distinguish uncertainties in our knowledge of basic **parameters** and choices of **models**.

Examples for parameter uncertainties:

- axial mass within CCQE,
- axial mass in nucleon-Δ transition matrix element.

These are *safe* handles to use in experimental analysis.

Example of *model uncertainty*:

- Fermi gas versus spectral function

No matter how much one modifies FG model free parameters (Fermi momentum, binding energy), results are very different from spectral function (see later for details).

Uncertainties: models and parameters

In the data analysis and in systematic error evaluation often ad hoc parameters are introduced lacking a clear physical interpretation:

- κ parameter introduced by MiniBooNE to cure low Q^2 data/MC discrepancy,
- W-shape parameter used in T2K to cover MC/data disagreement in pion production.

A necessity to use such parameters reflects deficiencies of models used in MCs. This should give motivation to improve them.

Models used in MCs (GENIE, NEUT, NUANCE)

- Llewellyn-Smith with dipole axial FF for CCQE,
- Rein-Sehgal for single pion production,
- custom made models in the RES-DIS transition region
  - (WARNING: definitions of RES and DIS are in each MC different),
- Yang-Bodek recipé for DIS (strictly speaking: *more inelastic* events),
- Fermi gas for Fermi motion and Pauli blocking,
- cascade models for FSI.

These ingredients did not change much during last 10 years.

Evolution of MCs

Major MCs evolve rather slowly.

There are many reasons for that:

- these are complicated codes,
- usually, there is just one person who keeps control of a code,
- conservative approach is something obvious; each modification can lead to side effects which must be carefully analyzed.

MC codes (NuWro) and approaches (GiBUU) not yet used by experimental groups are more flexible to test new pieces of theory.

Do we need better?

There are indications that we really need substantial upgrades of MCs:

- a hypothesis of a large multinucleon ejection contribution to what MiniBooNE identified as CCQE events:
  - MB did not investigate final state protons,
  - several theoretical computations of the effect,
  - an important impact on neutrino energy reconstruction (oscillations is an energy dependent phenomenon!);
- large spectral function uncertainty (introduced as SF/FG) in the T2K analysis,
- persistent problems in low Q^2 region,
- MC/data pion production discrepancy reported by MiniBooNE,
- discrepancy between Rein-Sehgal and new models for coherent pion production.

Can we do better?!

Yes.

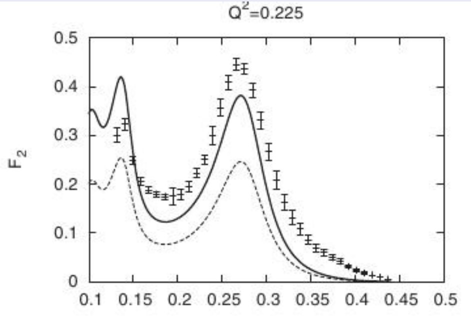
We know that some of the models used in neutrino MCs can be replaced by better!

A strategy:

- use knowledge accumulated in electron scattering experiments,
- use theoretical developments e.g. for coherent pion production.

How to improve models – pion production

Pion production in the Δ region.



Original Rein-Sehgal model has rather inaccurate vector FF.
Dashed line: prediction of the model for F_2.
Solid line: results with improved vector FF (still within RS model).

[from: K.M. Graczyk, JTS, Phys. Rev. D77 (2008) 053001, Erratum-ibid. D79 (2009) 079903].

There is still a room for a non-resonant contribution!

How to improve models – pion production (2)

Analysis of ANL and BNL data implies that original RS axial FF should be replaced by:

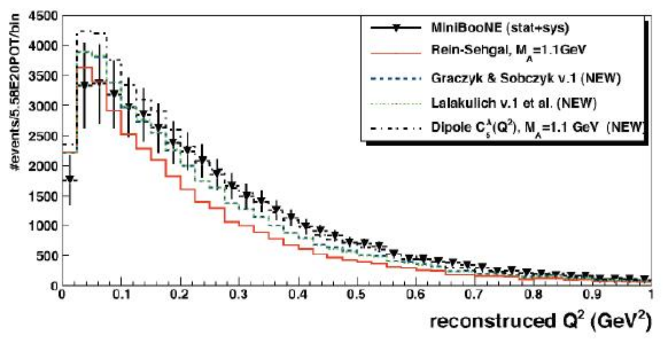
$$\tilde{G}_A^{\mathrm{RS,new}}(W,Q^2) = \frac{\sqrt{3}}{2}\left(1+\frac{Q^2}{(M+W)^2}\right)^{1/2} \times\left[1-\frac{W^2-Q^2-M^2}{8M^2}\right]C_5^A(Q^2).$$

$$C_5^A(Q^2) = \frac{C_5^A(0)}{(1+\frac{Q^2}{M_a^2})^2}, \qquad C_5^A(0) = 1.2, \qquad M_a \approx 0.94\ \mathrm{GeV}.$$

[from: K.M. Graczyk, JTS, Phys.Rev. D77 (2008) 053001, Erratum-ibid. D79 (2009) 079903].

How to improve models – pion production (3)

An analysis done for MiniBooNE suggest that one arrives at a much better agreement with the data:



[from J. Nowak presentation at NuInt09].

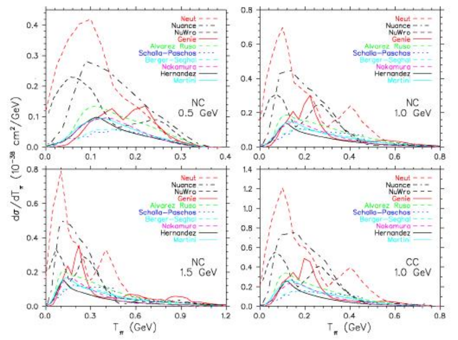
How to improve models – pion production (4)

It is probably necessary to re-examine description of the non-resonant contribution in the Rein-Sehgal model using a model of [J.Nieves et al Phys. Rev. D76 (2007) 033005].

This requires further studies.

How to improve models – coherent pion production

All the MCs (including NuWro :( ) rely on Rein-Sehgal model with verious modifications and predictions are rather remote from theoretical state-of-art computations.



[from S. Boyd, S. Dytman, E. Hernandez, JTS and R. Tacik, AIP Conf.Proc. 1189 (2009) 60].

How to improve models – spectral function (1)

Consider CCQE on nuclear target in impulse approximation.
The final state is assumed to be (a nucleon is decoupled from the remnant nucleus):

$$|f(p_f)>=|R(p_R)>\otimes|p'>.$$

It is easy to show that:

$$\frac{d^2\sigma}{d\omega dq}=\frac{G_F^2\cos^2\theta_C q}{4\pi E_\nu^2}L_{\mu\nu}W^{\mu\nu}$$

$$W^{\mu\nu}=\int dE\int d^3p\frac{\delta(\omega+M-E-E_{p'})}{E_pE_{p'}}H^{\mu\nu}(\vec{p}+\vec{q},\vec{p})P(E,\vec{p})$$

$L_{\mu\nu}=2\left(k_\mu k'_\nu+k'_\mu k_\nu-k\cdot k' g_{\mu\nu}-i\varepsilon_{\mu\nu\kappa\lambda}k^\kappa k'^\lambda\right)$, $H^{\mu\nu}$ is the free nucleon hadronic tensor.

How to improve models – spectral function (2)

In general:

$$P(E,\vec{p}) \equiv \sum_R \delta(M_A - E_R - M + E)| < R(\vec{p}_R)|a(\vec{p})|i(M_A) > |^2$$

$$\int d^3p \int dE \; P(E,\vec{p}) = A.$$

$\frac{1}{A}P(E,\vec{p})$ has a probabilistic interpretation.

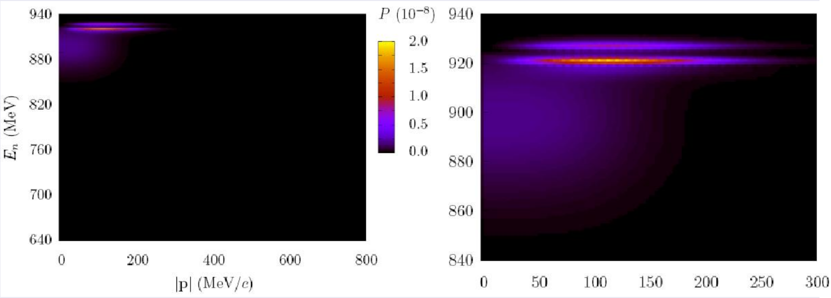
- in the Fermi gas model, $P(E,\vec{p})$ is characterized by two parameters: Fermi momentum k_F and binding energy B:

$$P(E,\vec{p}) = \frac{3A}{4k_F^3} \cdot \Theta(k_F - |\vec{p}|)\delta(E - B + \sqrt{M^2 + \vec{p}^2})$$

- typically both k_F and B are fitted to electron scattering data.

How to improve models spectral function (3)

Much better choice is spectral function (SF).
Below, the oxygen SF as calculated by Omar Benhar:

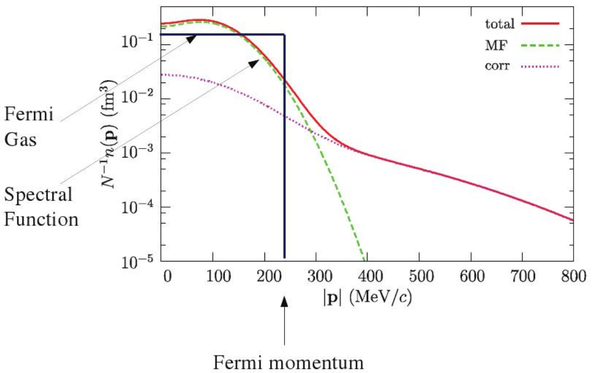


Shell model orbitals are clearly seen.

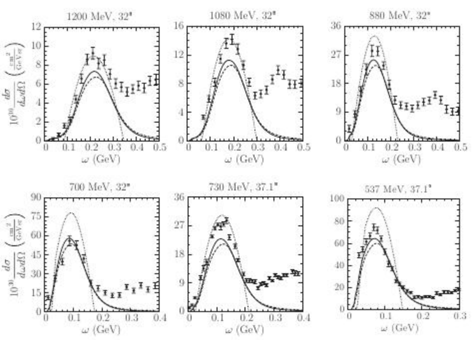
	$1s_{1/2}$	$1p_{3/2}$	$1p_{1/2}$
E	45	18.44	12.11

How to improve models – spectral function (4)

A characteristic feature of SF is long momentum tail coming from correlated pairs.



How to improve models – SF in action



Electron scattering off Oxygen. Solid line - SF, dotted line - FG.

[from: A.M. Ankowski, JTS, Phys. Rev. C 77 044311 (2008)]

We clearly see QE peak, Δ peak (or Δ tail). In theoretical computation only QE dynamics is used so that one expects results to be below the data to leave a room for other contributions.

How to improve models – NuWro SF implementation

- Explicit cross section formula is known: simply make integration in the MC way!
- Code must be little slower than for FG: there is an extra integration,
- Carbon, Oxygen, Iron – tables from Omar Benhar; Calcium, Argon – Ankowski& JTS (performance for electron scattering is very good).
- Basically, no free parameters (what theorists like), but...
  - Fermi momentum in Pauli blocking
  - relative size of SRC contribution?
  - parameters in FSI?
- there are other approaches to include nuclear effects in a proper way (see later), but SF is similar to FG and seems to be a preferable one

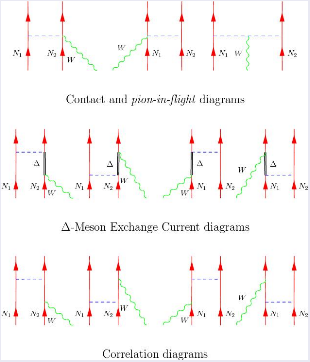
How to improve models – meson exchange current (MEC) (1)

As mentioned before, there are many indications that CCQE events may be quite often confused with MEC events which occur only in neutrino-nucleus scattering and not in neutrino-nucleon interactions.

Kinematics for those events is different than for CCQE and if neutrino energy is inferred based on CCQE assumption a large bias is introduced.

How to improve models – MEC (2)

Think about more complicated Feynman diagrams:

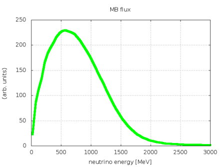


$$J^{\alpha}_{2body} \sim a^{\dagger}(p_1')a^{\dagger}(p_2')a(p_1)a(p_2)$$

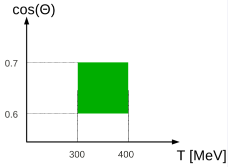
can create two particles and two holes (2p-2h).

How to improve models – MEC (3)

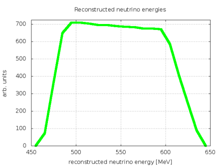
MEC and neutrino energy reconstruction



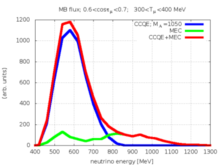
Consider MB flux...



... and a particular 2D bin.



E_{rec} using CCQE formula.



E_{true} from CCQE and MEC events.

[from J. Morfin, JTS, poster presented at NEUTRINO 2012, Kyoto].

How to improve models – MEC

Some controversy about a size of the effect, relevance for neutrinos, antineutrinos.

It is not enough to study muons.

One must analyze nucleons in the final state.

For that one needs theoretical predictions.

FSI effects are very important and a model giving predictions for nucleons after MEC events must be combined with a MC event generator (or hadronic transport code like GiBUU).

How to improve models – MEC

Based on JTS, Phys.Rev. C86 (2012) 015504

A main idea: use as an input any model which gives predictions for the two-body contribution to the muon inclusive cross section and make predictions for the final state nucleons.

How to improve models – MEC

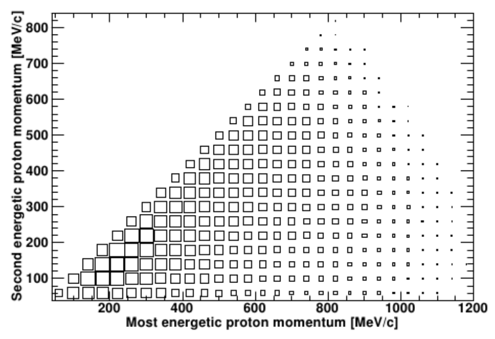
We use only muon information.

- We know muon's kinetic energy and production angle.
- Equivalently, we know momentum and energy transfer.
- We select 2(3) nucleons from the Fermi sea.
- We add the energy and momentum transfered to the hadronic system.
- We perform a boost to the hadronic center-of-mass frame (CMF).
- In the CMF we select isotropically 2(3) nucleons in the final state.
- We perform boost back to the laboratory frame.
- Energy balance must be consistent with FSI model.
- Event's weight is given by muon differential cross section.

How to improve models – MEC

An example of prediction. Neutrino energy is 750 MeV.

Look for momenta of two knocked-out protons:



NuWro

- the project started $\sim$ 2005 at the Wrocław University; an important encouragment from Danka Kiełczewska from Warsaw,
- Main authors: C. Juszczak, J.Nowak (at early stage; now at the Minnesota University), T. Golan, JTS
- the code is written in C++.
- can handle various target, fluxes
- has a detector interface (back-up slides)
- MicroBooNE is using NuWro to simulate neutrino events in its detector, and LArSoft more generally will use it as one of its neutrino generators [from E. Church]. Great!

NuWro – intranuclear cascade model

- in the Δ region based on a model of Oset et al with density dependent cross sections for pion-nucleon scattering and absorption

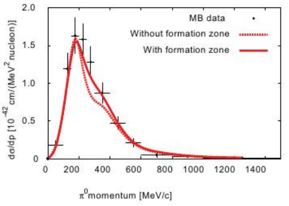


FIG. 16. (Color online) MiniBooNE (neutrino mode): NC $1\pi^0$ production as a function π^0 momentum.

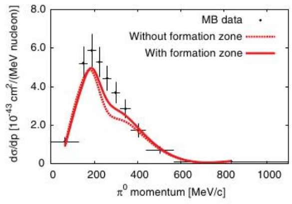


FIG. 17. (Color online) MiniBooNE (antineutrino mode): NC $1\pi^0$ production as a function π^0 momentum.

[from T. Golan, C. Juszczak, JTS, Phys.Rev. C86 (2012) 015505].

Formation zone means mostly an effect of finite Δ life-time.

- there is a variety of models for FZ, NEUT and GENIE approaches are different.

Discussion – generalities

It seems that most *obvious* improvements of MCs should be:

- implementation of one of the MEC models
- upgrade of Rein-Sehgal model for pion production
  - or to avoid RS, as is done in NuWro!
- replacement of FG by SF
- implementation of one of the modern COH models

In most cases improvements will require a close experimental group/MC authors collaboration!

Discussion – MEC

- there are many models with rather different predictions
- it is necessary to look for the effect (proton tracks, vertex activity) in order to select a proper model
- according to MB this is a huge effect, 25% of CCQE or so, but still can be difficult to identify without ambiguity
- a biggest challenge: description of FSI effects with cascade models must be quite reliable.

Discussion – pion production

- it is rather difficult to learn about primary pion production interaction from study of pions in the final states (with FSI effects included)
- a possibility to compare results with the same flux and different nuclear targets available in MINERvA gives a unique possibility to separate (and then subtract) nuclear effects
- also PIANO experiment should help to develop better cascade models.

Discussion – SF and alternatives

- there are alternative models to include nuclear effects for CCQE
- each model has a kinematical domain where it works well
- SF seems to be a preferable choice because it is similar to FG and relatively easy to understand
- NuWro offers implementation of two other models (back-up slides)
  - momentum dependent nuclear potential (similar to what is there in GiBUU)
  - *random phase approximation* (a misleading name; improves results of FG in the low Q^2 region)
- it would be great to make a comparison of all three models with high statistics CCQE data,
  - separation of CCQE requires identification of MEC!

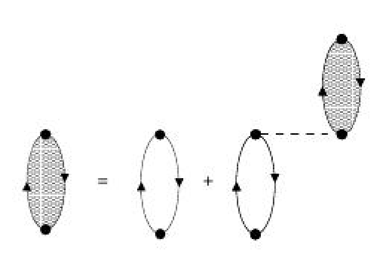
Thank you!

I thank Gabe Purdue for many useful comments on earlier versions of this presentation!

Back-up slides

NuWro – random phase approximation (RPA).

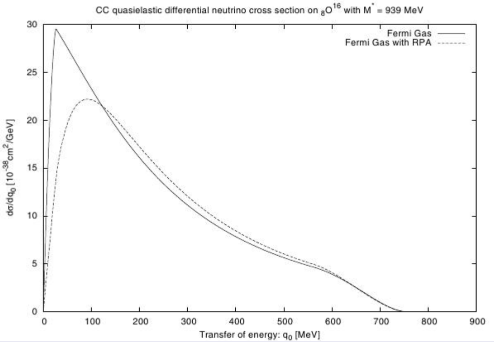
Still another strategy to include nuclear effects beyond FG model. One includes residual nucleon-nucleon interactions and performs summation over ladder type diagrams:



Nieves et al J. Nieves, I. Ruiz Simo, M.J. Vicente Vacas, Phys.Lett. B707 (2012) 72 result is that FG+RPA+MEC together allow for a good agreement with MiniBooNE 2D CCQE data with $M_A = 1.007 \pm 0.034$ GeV (with low momentum transfer cut) or $M_A = 1.077 \pm 0.027$ GeV (without the cut).

NuWro – RPA

NuWro implementation follows: [K.M. Graczyk, JTS, Eur.Phys.J. C31 (2003) 177].



NuWro – effective momentum dependent potential

Both initial state and final state nucleon experience nuclear environment which can be approximated by means of effective momentum dependent potential.

Kinematics (energy conservation) becomes rather involved.

NuWro implementation: [C. Juszczak, J.A. Nowak, JTS, Eur.Phys.J. C39 (2005) 195].

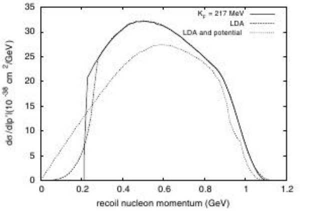


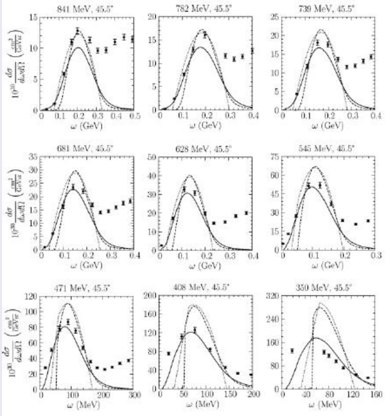
Fig. 7. Recoil nucleons momentum distribution for quasi-elastic neutrino-argon scattering. The incident neutrino energy is E_ν = 700 MeV

LDA - local density approximation; effective potential leads to much more realistic spectrum; FSI effects are not included.

How to measure the two-body current contribution?

- Of interest are CCQE-like events, with no pions in the final state; one needs a strong veto on pions.
- One can use the information contained in reconstructed proton tracks and also in the *vertex activity*.
- It is better to have a low threshold for reconstruction proton tracks.
- The quality of FSI model is very important, real pion absorption seems to be the most important background.
- Observables like integrated kinetic energy seem to be less affected by FSI.

SF in action

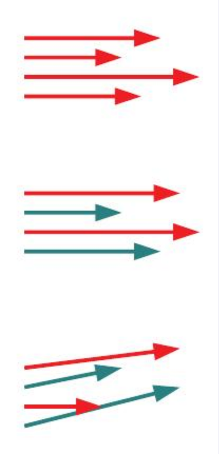


Calcium. Solid line - SF, dotted line - FG, dashed line - still another model, similar to FG.

NuWro: flux

Three options:

- one flavour neutrinos, fixed direction, an arbitrary energy distribution
- a mixture of flavours, each one with its own energy distribution
- neutrinos retrieved from data files (arbitrary flavours, directions, energies)



NuWro: target

Three options

- a single isotope model (including also a single nucleon mode)
- a mixture of isotopes (composition defined by relative weights)
- detector's geometry given as a root Geometry object.
  - geometry is read from a file containing the detector's definition
  - region of interest can be limited to a box by specifying its center and halfsize vectors.